625

VOLUME 81 SEPARATE No. 625

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

FEBRUARY, 1955

INVESTIGATING GROUND WATER BY APPLIED GEOPHYSICS

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HYDRAULICS DIVISION

{Discussions open until June 1, 1955}

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Printed in the United States of America

Headquarters of the Society
33 W. 39th St.
New York 18, N. Y.

PRICE $0.50 PER COPY

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This paper was published at 1745 S. State Street, Ann Arbor, Mich., by the American Society of Civil Engineers. Editorial and General Offices are at 33 West Thirty-ninth Street, New York 18, N. Y.

INVESTIGATING GROUND WATER BY APPLIED GEOPHYSICS

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ABSTRACT

With the development and improvement of geophysical methods for petroleum and mineral exploration has come the recognition that many of these methods may be adapted to ground water investigations. Continued demands for ground water as a water supply for expanding population, irrigation, and industrial needs undoubtedly will foster greater use of geophysical methods for ground water location, analysis, and development in the future. In this paper an attempt has been made to present brief summaries of geophysical approaches that now have usefulness in the ground water field. Basic principles, methods, applications, and examples are included. A selective bibliography concludes the paper.

INTRODUCTION

Applied geophysics may be defined as the scientific measurement of physical properties of the earth's crust for investigation of mineral deposits or geologic structure. The terms geophysical exploration and geophysical prospecting are used synonymously. Many of the methods of applied geophysics relate to an important civil engineering problem—the location, analysis, and development of ground water. Although the fundamental laws of physics utilized are not new, the science has undergone in the past 30 years a tremendous expansion. Oil was first discovered by geophysical methods in 1926. Since then the economic pressures for the location of petroleum and mineral deposits stimulated the development and improvement of many geophysical methods and associated equipment. Because the location and exploitation of ground water did not carry similar commercial rewards, application of these methods to ground water was not economically feasible. Then, too, other methods of ground water location such as geologic reconnaissance and test drilling generally were successful in finding ground water. In recent years, however, the refinement of geophysical techniques and an increasing recognition of the advantages of these methods for ground water studies have brought about a change in this situation. Today many federal, state, and municipal organizations responsible for meeting water supply demands are employing geophysical methods for ground water investigations.

Applied geophysics is based upon detecting differences, or anomalies, of physical properties within the earth's crust. Those properties most commonly studied are density, magnetism, elasticity, electrical conductivity, temperature, and radioactivity. Various geophysical methods measure differences in these properties. Experience and research have enabled these differences to be interpreted in such terms as geologic structure, rock type

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and porosity, water content, and water quality. In most instances the measurements are indirect indications of information desired. This is particularly true for ground water investigations. Geophysical measurements may suggest, for example, location of an aquifer, its porosity, and the quality of its contained water; but other information in the area is necessary for a correct interpretation. Applied geophysics should be regarded as a supplemental investigative tool for the ground-water hydrologist rather than a sole means to an end.

The following sections include brief summaries of some of the geophysical approaches—their basic principles, methods, applications to ground water, and examples. Only those methods having well-defined applicability to ground water investigations are included. Other methods such as gravity, magnetic, and radioactive, are not included because they have been applied on a more limited basis. Thus, gravity and magnetic measurements have been used successfully to map buried valleys forming good aquifers and the impermeable ridges limiting these valley flows; and in recent years neutron and gamma ray well logging have been extended from petroleum to water supply investigations. The reader is referred to any of the excellent recent texts on geophysical exploration(1, 2, 3)[2] for more detailed descriptions of all methods.

Indications are that applied geophysics will be a more valuable source of subsurface data for many civil engineering problems in the future. Besides applications to ground-water hydrology, foundation conditions, bedrock locations, tunnel locations, gravel and soil deposits, and highway locations(10, 11, 14, 15, 51) are all problems benefited by applied geophysics.

Surface Methods

Electrical Resistivity

The electrical resistivity of a rock formation limits the amount of current passing through the formation when a specified potential is applied. The electrical resistivity of a material is the resistance in ohms between opposite faces of a unit cube of the material. If a material of cross-sectional area A and length L has a resistance R, then its resistivity may be defined as $\rho = \frac{RA}{L}$. In the metric system the units of resistivity are ohm-cm^2/cm, or ohm-cm.

Resistivity of rock formations varys over a wide range, depending upon the material, density, porosity, pore size and shape, water content and quality, and temperature. There are no fixed limits for resistivities of igneous, metamorphic, and sedimentary rocks. In relatively porous formations the resistivity is controlled more by the water content and quality within the formation than by the rock resistivity itself. For aquifers composed of unconsolidated materials, the resistivity of the ground water governs, while that of the solid material may be neglected. Aquifer resistivity can be expressed in terms of resistivity of the ground water and of porosity for uniform packings of spherical mineral grains. If ρ is the aquifer resistivity, ρ_w is that of the ground water (assumed to fill all of the voids), and v_i is the pore volume, then $\frac{\rho}{\rho_w} = \frac{3 - v_i}{2v_i}$ (2). Observed resistivities

2. Numbers in parentheses refer to items of the Bibliography at the end of this paper.

agree closely with those indicated. The above relationship applies only for isotropic conditions. For anisotropic conditions the orientation of the current with respect to stratifications will produce resistivity differences.

Subsurface resistivity values can be obtained from surface measurements. The procedure involves the measurement of a potential difference between two electrodes on the surface resulting from an applied electric current through two other electrodes. The electrodes are commonly placed in line, with the potential electrodes inside the current electrodes. Various arrangements of electrodes have been devised. Two of the most common are the Wenner (Gish-Rooney) and the Lee partitioning methods. In the Wenner arrangement the potential electrodes are located at the third points between the current electrodes. The Lee partitioning method uses a fifth electrode placed in the center with potential measurements made between it and the potential electrodes individually. The resistivity is given by the ratio of voltage to current times a spacing factor. For the Wenner arrangement, the formula $\rho = 2\pi a \frac{V}{I}$ is applicable, where a is the distance between two adjacent electrodes.

If the resistivity is everywhere uniform in the subsurface zone beneath the electrodes, the lines of current flow will form a pattern of circular arcs, according to potential theory, connecting with the current electrodes. The resistivity will be the same for any electrode spacing. For multiple layers of different resistivity, modified flow patterns result because of the relative resistivity differences. As a first approximation, the electrode spacing in the Wenner method is commonly assumed to be equal to the effective depth of resistivity measurement.

Changes of resistivity at greater depths have only a slight effect on a resistivity-depth curve as compared to those at shallower depths. The interpretation of a resistivity-depth curve in terms of subsurface conditions is a complex and frequently difficult problem. Several methods of properly interpreting resistivity curves, based upon analytical and model studies have been devised; descriptions may be found in the pertinent literature (see Bibliography).

Resistivity surveys can cover either vertical investigations at selected points by varying electrode spacings or they can be used to prepare iso-resistivity maps of an area. The latter procedure requires the use of a constant electrode spacing which measures resistivities at a particular depth of interest, such as an aquifer, over a wide area. Areal resistivity changes can be interpreted in terms of aquifer limits and changes in ground water quality, while variable depth surveys may indicate aquifers, water tables, impermeable formations, and bedrock depths.

Any factors which disturb the electrical field in the vicinity of the electrodes may invalidate the resistivity measurements. Buried pipe lines, cables, and wire fences frequently limit resistivity surveys. Near-surface saturation, such as immediately following a heavy rain, makes measurements difficult to obtain; while on the other hand extremely dry conditions may necessitate moistening the ground around electrodes to establish proper earth contact.

Resistivity Applications

Resistivity surveys have been made on a world-wide basis. Paver[30, 32] has summarized work in the Middle East and Africa, including Palestine,

Syria, Cyprus, Greece, Malta, Lebanon, Iraq, Transjordan, Arabia, Egypt, Kenya, Uganda, Tanganyika, Somaliland, Southern Rhodesia, and Union of South Africa. Based upon resistivity surveys, successful wells have been drilled in many of these countries in 75 to 90 percent of all cases. Thus, Loehnberg and Loewenstein[29] claimed 85 percent success in Palestine; Way[42, 43, 44], 80 percent in Uganda. From exploratory work in Southern Rhodesia, Shaw[35] reported, "The cost of operating the resistivity method is negligible compared with that of drilling and the potential savings from its use are very large." Other resistivity surveys have been conducted in Nigeria,[41] Spain and Peru,[11] and England.[33]

In Australia, Bruckshaw and Dixey[21] used the resistivity method for finding perched water tables, alluvium-filled valleys, water pockets in weathered crystalline rocks, and ground water boundaries such as faults, fracture-zones, and dikes. Resistivities below 600 ohm-cm proved to be saline waters, while relatively low resistivities greater than this indicated either potable water or low porosity rocks containing saline water. Paver[32] reported 2000 ohm-cm as the limiting resistivity for saline water, except in instances of water-saturated clayey materials. He also found that rough correlations existed between resistivity and water yield, and that iso-resistivity maps provided useful information in locating new wells.[31] In Uganda the near-surface geologic structure consists of laterite, decomposed rock, and solid rock, overlying igneous and metamorphic rocks. Resistivity curves in this area were classified into five types from which criteria were derived for ascertaining water potentiality.[44]

Resistivity surveys can be used to delimit underground bodies of salt water and extent of sea water intrusion. In the Hawaiian Islands, where fresh water floats on underlying sea water in the porous lava formations, Swartz[37, 38, 39, 40] has been able to locate the depth of the fresh water-salt water interface with resistivity measurements. At five sites where verifications later were made by drilling, the predicted and observed depths to interface agreed on the average to within less than one foot. Boundaries of sea water intrusion have been traced with the method in Western Germany[25] and near El Paso, Texas.[34] In the latter study resistivity-traverses were laid out with stations at 1500-foot intervals and depths were measured to 1000 feet.

In the United States resistivity surveys for ground water appear to be increasing in number. Work has been reported in Arizona,[26] California,[16] Illinois,[9, 22, 46] Indiana,[20] Michigan,[27] Nevada,[28] New Mexico,[41] Texas,[34] and Wisconsin.[36] Accurate determinations of depth to ground water table were obtained from resistivity curves in two Arizona canyons.[26] An experimental investigation on the utility of resistivity surveys for locating ground water supplies was carried out in the glacial drift of southern Michigan.[27] Results showed that the method located low-resistivity deposits which test drilling verified as promising aquifers. Costs were small, giving a direct saving in terms of the number of test holes required. Studies by Tattam[41] in New Mexico and abroad led to conclusions that the ground water table was capable of definition as a discontinuity on the resistivity curve, that interpretations varied with geologic conditions, that absolute salinities of ground water could not be measured, but that relative salinity variations within a geologically uniform area could be detected.

The record of the Illinois State Geological Survey provides an excellent illustration of the success of resistivity surveys in locating ground water supplies.[22, 46] At least 43 municipalities in the central portion of the state

derive their total water supply from deposits of sand and gravel discovered by resistivity methods. Test drilling of recommended sites has proved the correctness of interpretation of resistivity measurements in about 92 percent of the cases. The work is performed using resistivity traverse profiles, depth profiles, and iso-resistivity maps. In the last method grids are laid out in the area for study and resistivity measurements are made at a constant electrode spacing through the glacial drift overlying the bedrock (usually less than 100 feet deep). Preglacial channels of outwash sand and gravel containing water, dry gravel terraces, and near-surface bedrock configurations are readily identified.

An unusual application of the electrical resistivity method, which holds much promise, has been reported by the U. S. Bureau of Reclamation.(23) This consists of locating areas of seepage along canals for canal-lining programs. Using the Wenner configuration, both depth and traverse profiles of resistivity are obtained paralleling canals under study. For canals with only seasonal flows, measurements taken during periods when the canal is dry may be compared with those taken during periods when the canal is flowing. Results, when combined with geologic evidence, are helpful in delineating seepage areas.

Seismic Refraction

The seismic refraction method involves the exploding of a small dynamite charge on the earth's surface and measuring the time required for the resulting sound, or shock, wave to travel known distances. Seismic waves follow the same laws of propagation as light rays and may be reflected or refracted at any interface where there is a change in velocity. Seismic reflection methods provide information on geologic structure thousands of feet below the surface, whereas seismic refraction methods—of interest in ground water studies—cover only a few hundred feet in depth. The travel time of a wave depends upon the media through which it is passing; velocities are greatest in solid igneous rocks, and least in unconsolidated materials. Wave velocities in unconsolidated, unsaturated aquifers are the order of 1500-3000 ft/sec, 3000-6000 ft/sec in saturated aquifers, and 6000-10,000 ft/sec in poor aquifers with appreciable clay or silt content.

Changes in seismic wave velocities are governed by changes in the elastic properties of the formations. The greater the contrast of these properties the more clearly can the formations and their boundaries be identified. In sedimentary rocks the texture and geologic history are more important than the mineral composition. Porosity tends to decrease wave velocity, while water content increases the velocity.

When a shot is fired, a spherical wave front expands outward from the shot point. It travels at a speed governed by the material through which it is passing. If a homogeneous unconsolidated material is assumed with a free ground water table, the wave upon reaching the water table will travel along this interface. As it travels along the interface a series of waves are propagated back into the unsaturated layer. At any distance on the surface, the first wave will arrive either directly from the shot point or from a refracted path. By measuring the time of the first arrival at varying distances from the shot point, a time-distance graph may be plotted. The slope of a line through the points indicates the wave velocity, while a change in slope indicates an interface. The interfacial depth may be computed as a function of the formation velocities and the distance to the intersection of the two slopes. Multilayered problems may be solved in a similar manner. Different

surface elevations, sloping formations, faults, and changes in the interfacial configuration require special analysis. Computational procedures may be found in the published literature (see Bibliography).

The field procedure for seismic refraction investigations has been extremely simplified with the help of modern instrumentation. Shot holes are hand-augured to 3-5 feet deep. A dynamite charge ordinarily of less than one pound is placed in the hole and the hole back-filled. Geophones, which receive the shock wave and convert the vibration into electrical impulses, are spaced in a line from the shot point 10-50 feet apart. The geophones are connected by an electrical circuit to amplifiers and a recording oscillograph which automatically records the instant of firing and the first arrivals of waves at each geophone. Depth determinations to 200-300 feet are typical with this equipment, although satisfactory work is possible to depths of 2000 feet.

Interpretation of seismic refraction data assumes homogeneous layers bounded by interfacial planes. Where no distinct boundary exists, but rather a gradual transition zone, this appears as a curve on the graph. Fortunately, water tables approximate planes, so that many of the problems imposed by irregular configuration of geologic structure are avoided. Efficient use of the method requires skill in proper interpretation of rock materials, depths, and irregularities. Previous knowledge of subsurface materials and configurations aid in proper analysis of field records. The actual presence of ground water is difficult to determine without supplemental information; overlapping of velocities in saturated and unsaturated zones being primarily responsible. Seismic wave velocities must increase with depth in order to obtain satisfactory results. The seismic refraction method can eliminate rapidly and economically areas unfavorable for test drilling. It is not readily adapted to small areas. Minimum distances of several hundred feet are needed for seismic profiles in different directions. Local disturbances, as from highways, airports, or construction sites interfere with seismic work.

Seismic Applications

Incidental to foundation explorations by seismic refraction for proposed dams in the Ohio River Basin by the Corps of Engineers, the location of ground water tables frequently was possible.[48] Determinations were based on velocity differences between saturated and unsaturated overburden.

The work by Linehan and others[47, 49, 50] in locating ground water supplies by the seismic refraction method in New England shows notable examples of the applicability of the method. This work has been directed toward finding gravels of sufficient depth and porosity to allow easy flow of ground water, which could be confirmed by test drilling. Locations in the glacial drift found to have bedrock close to the surface or steeply sloping bedrock could be discarded at once. Successful results have been obtained at Concord, Northbridge, Southbridge, Springfield, and Weston, Massachusetts, and at Naugatuck, Connecticut.

Well-Logging Methods

Resistivity Logging

The resistivity of rock formations and ground waters have been discussed under surface methods. Here the purpose is to apply this knowledge to instruments lowered into a well to obtain information regarding the strata intersected by the well.

From current and/or potential electrodes within a well, the electrical resistivity of the surrounding medium may be obtained. Several electrode arrangements have been devised to give details of changes of resistivity with depth. Some systems are entirely independent of the surface and measure only within a well. The four-electrode arrangement, which includes two potential and two current electrodes suspended in a well from the surface, yields precise results of strata thickness. The resistivity measured is a composite value of the material between the two electrodes.

In rotary-drilled wells account must be taken of the drilling fluid resistivity in relation to that of the surrounding strata. This may be done by varying the spacing between adjacent current and potential electrodes so that the resistance of the drilling fluid has a minimum effect on the resistivity. Different electrode spacings also provide more accurate resistivities in beds of varying thickness.

Resistivity logs may be used to determine specific resistivities of strata, or they may be used qualitatively to indicate relative changes of importance. As mentioned before, the resistivity of an unconsolidated aquifer is controlled primarily by the porosity, packing, water resistivity, and saturation. Estimates of the porosity are possible if the formation and water resistivities are known. The relation is of the form

$$\frac{\rho}{\rho_w} = \frac{1}{P^m}$$

where P^m is a formation factor consisting of P, the porosity, and m, a void-distribution (cementation) factor. From laboratory tests, where ρ, ρ_w, and P are known, the value of m may be determined. Tests of many samples of different unconsolidated sands gave an average m of 1.55, with a range for different formations of 1.43 to 1.65.(60) Porosity determinations can be made from field measurements of ρ and ρ_w, together with an appropriate value of m.

Resistivity of a ground water depends upon ionic concentration and ionic mobility of the salt solution. This mobility is related to the molecular weight and electrical charge, so that large differences exist for various compounds; for example, the ion mobility of a sodium chloride solution is several times that of a comparable calcium carbonate solution. In a study of the ground water bordering San Francisco Bay,(64) it was found that the salinity-resistivity relation for various dilutions of sea water was not the same as that of ground water. The differences were attributed to different relative concentrations of ions. At 25°C the resistivity for several natural ground waters in Louisiana was related to S, the total dissolved solids, by

$$\rho = 559{,}000\ S^{-.986}$$

where ρ is measured in ohm-cm and S in ppm.(60) This may be compared with

$$\rho = 854{,}100\ S^{-1.050}$$

which closely fitted a collection of ground and surface waters from several Western states.[3] The resistivity-concentration equation for NaCl solutions,

3. Richards, L. A., Diagnosis and Improvement of Saline and Alkali Soils, U. S. Regional Salinity Laboratory, Riverside, Calif., 157 pp., 1947.

expressed in the same units, is[4]

$$\rho = 413{,}700\ S^{-.970}$$

which indicates a smaller resistivity for the same concentration of total dissolved solids. Other single salt solutions have different relations, some differing by 100 percent or more in resistivity for given concentrations.

Jones and Buford[60] have extended the usefulness of the resistivity log by their procedure for estimating the chemical analysis of a well water from its resistivity. Estimates were prepared on the basis that chemical composition in an extensive aquifer follows a systematic pattern of variation with total dissolved solids. Typical graphs showing ion concentrations versus total dissolved solids, prepared for each of the major aquifers, enabled estimates to be made knowing the source aquifer and the measured ground water resistivity.

Temperature affects the resistivity of ground water. This effect is derived from the greater ionic mobility associated with a decrease in viscosity. Hence an inverse relation exists with the resistivity of ground water increasing with decreasing temperature. For ground water and sea water the effect amounts to a change of about 2 percent in the resistivity for each 1°C change in temperature.

Potential Logging

The potential method makes use of natural ground potentials found in the earth. The potentials are sometimes referred to as self-potentials, or spontaneous potentials. The method is simple, consisting of measurements in millivolts on a recording potentiometer of two like electrodes either lowered at a given interval into a well, or one electrode lowered and the other connected to the ground surface. The interpretation, however, is difficult and of a qualitative nature. The exact nature of phenomena giving rise to observed potentials is not entirely known. Electrofiltration resulting from the flow of water through porous media,[65] electrochemical potentials arising from fluid concentration differences, energy from chemical reactions occurring at formation boundaries, oxidation, and pH gradients have been suggested as possible causes.

It is common practice to obtain potential and resistivity logs at the same time. The two logs usually exhibit similar changes with depth, except that the amplitude of the resistivity log is several times that of the potential log. The pair of logs will frequently supply subsurface information not possible from either alone. Table I lists typical indications of potential and resistivity logs in different formations.[59]

Table I—Relative Potential and Resistivity Values of Various Formations

Formation	Potential	Resistivity
Shale; clay	None	Low
Fresh water sand	Low or moderate (-), or (+)	Moderate or high
Salt water sand	High	Low
Cemented sandstone	Low	High

4. National Research Council, International Critical Tables of Numerical Data, Physics, Chemistry and Technology, v. VI., McGraw-Hill, New York, p. 233, 1929.

Potentials may be either positive or negative, depending upon the relative salinities of the drilling fluid and of the ground water. The equation $P = K \log \frac{\rho_f}{\rho_w}$ may be applied, where P is the potential, ρ_w is the resistivity of the ground water, ρ_f is the drilling fluid resistivity, and K is a constant governed by the chemical composition of the two fluids and by the character of shale adjoining the permeable bed. A value of K = 70 has been found satisfactory in California.(59)

Logging Applications

Most electric welling-logging operations today are in the United States. Wells have been studied in California,(59, 64) Illinois,(54, 56) Louisiana,(62, 63) Texas,(57, 58, 61, 66) and undoubtedly several other states.

In the San Joaquin Valley of California an estimated 50 percent of the rotary-drilled wells are electrically logged.(59) Logs are obtained in about one hour in an uncased well filled with drilling fluid. They have been found beneficial for determining formation types, for locating aquifers, for proper placement of perforations, and for correlating formations from well to well.

For estimating salt concentrations, resistivity logs of well waters only may be quite useful. In the sea water intrusion area bordering the southern portion of San Francisco Bay, such logs were useful in locating sources of contaminating water in wells.(64) Wells which intersect both fresh and salt water aquifers may act as sources of contamination because of the interconnection. The circulation under non-pumping conditions depends upon the relative hydrostatic heads, densities, positions, aquifer thicknesses, and the physical structure and condition of the well. Resistivity logs of well waters enabled these sources of saline circulation to be located for remedial action. The method has been used in Texas(61) for the same purpose.

Electrical logging has become an integral part of many exploratory drilling programs. Examples are those by the Geological Survey in Louisiana(62, 63) and in Texas.(57, 58, 66) In these studies the logs were used to determine bed sequences, to correlate aquifers, and to estimate changes in ground water quality.

Wide applications of electrical well logs have been reported by the Illinois State Geological Survey.(54, 56) These include location of productive aquifers, ground water contaminants, thieving zones (aquifers taking water from a well), lost drilling tools and well obstructions, stray earth currents producing electrolysis and corrosion; obtaining well logs where no records are available; research purposes; determination of rehabilitation possibilities of old wells; and checking positions of well casings. The electrical logs are supplemented by caliper and temperature logs, which record well diameters and ground water temperatures, respectively.

CONCLUSION

The foregoing discussion represents an attempt to indicate the chief geophysical methods applicable to ground water location, analysis, and development. Emphasis has been placed upon the fundamentals of each method, how they relate to ground water, what information each method is capable of supplying, and specific applications of each method. Details of field procedure, computations, and instrumentation have been omitted. These may be found in

the published literature and from organizations concerned with instrumental and operational aspects of applied geophysics.

It is well to emphasize that no geophysical method provides ground water information directly. It does provide indirect indications which may be interpreted in terms of underground hydrologic data. Correct interpretation requires supplemental data from well logs, geologic reconnaissance, or test drilling to substantiate the geophysical data. If the geologic situation is favorable for use of geophysical methods, the accuracy of results obtained depends to a large extent on the availability of supplemental data. Failure to recognize the importance of such data has done much to discourage the use of geophysical methods by ground water hydrologists.

Economically speaking, geophysical methods are proving their worth more now than at any time heretofore. This may be attributed to our better knowledge of the relationship of applied geophysics to ground water, to the more compact, more efficient, and more portable instruments available, and to the ever-increasing importance of adequate water supplies. Specific cost figures are difficult to generalize because of the many variables involved; however, in almost every instance where geophysical methods have been utilized, the investigator has clearly stated that the same information could not have been obtained by other methods except at much greater cost. Since much of our present knowledge is based upon trial-and-error efforts, organized research in this field may be expected to contribute to greater applications, improved instrumentation, and reduced costs. Dr. Meinzer's unqualified statement in discussing research needs of ground water hydrology is particularly apropos, "Methods of geophysical exploration must receive more study."[5] Similarly, a statement by The President's Materials Policy Commission, "Research aimed at applying modern know-how to making geophysical techniques simpler, cheaper, and in general more directly useful . . . could make a vast contribution to the nation's mineral resources picture."[6] applies equally well to ground water.

A bibliography on geophysical methods applied to ground water hydrology follows. It is selective in that only English-language references are included, that only papers having some obvious connection to ground water are included, and that no comprehensive literature search was conducted. In spite of a lack of completeness, it may be useful as a guide to engineers and students who wish to go further into the subject.

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